GLOBAL TRACTOGRAPHY OF MULTI-SHELL HARDI DATA

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TARGET AUDIENCE – Researchers working on tractography methods and microstructural modelling.

PURPOSE – Conventional fibre tracking techniques estimate the fibre directions in all voxels and then use a local stepping method to track the entire pathway. However, the sensitivity of these techniques to local estimation errors is a well-known issue, as well as ambiguous fibre configurations arising from the symmetry of the DWI data [1,2]. Global fibre tracking methods [2–5], on the other hand, aim to reconstruct the full track configuration that best explains the data as a whole. Current methods have been limited to single-shell HARDI data and use fixed models for the fibre response function. In this study, we extend the method of Reisert et al. [3] for multi-shell HARDI data and allow to use arbitrary fibre response functions, estimated from the data.

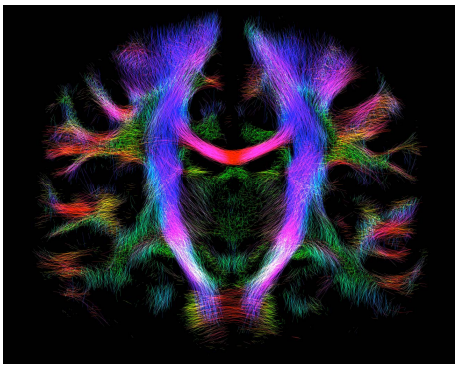
Fig. 1: Coronal slab (2.5mm) of the reconstructed tractogram.

METHODS – *Model:* As in [3], we model the global fibre configuration M as a set of discrete track segments and a set of connections between endpoints of these segments.
Forward problem: Given the model, we simulate the MR signal D' of multiple shells in q-space using a fibre response function K_b [6] estimated from the data (as opposed to [3] that uses the "ball-and-stick" model on single shell data). To this end, we reconstruct the fibre orientation distribution function (fODF) in every voxel as the sum of δ-functions in the spherical harmonics (SH) basis, oriented along the directions of all track segments in that voxel. Convolution of this ODF with a white matter (WM) kernel for every shell allows to evaluate the q-space signal along all gradient directions, and can be written as a matrix-vector multiplication of SH coefficients. Additionally, we introduce two isotropic terms that model the fractions of cerebrospinal fluid (CSF) and grey matter (GM) on all shells (including b=0s/mm^2). In summary, given the fibre ODF and the CSF and GM fractions, the simulated data of each shell equals

$$D'_b = K_b * \mathrm{fODF} + c_{csf,b}\, f_{csf} + c_{gm,b}\, f_{gm} \quad .$$

Inverse problem: Given the DWI data D, the ultimate goal is to reconstruct the fibre configuration M as the global optimum of the forward problem. Similar to [3], we use a simulated annealing scheme to minimize the sum of an external energy term $E_{ext} = \sum \|D - D'\|^2$, that equals the log-likelihood of the data given the model, and an internal energy term E_{int}, that measures the prior probability of the given configuration. The internal energy depends on length and curvature of the tracks and is defined identical to [3]. The external energy, on the other hand, depends on the forward problem and is redefined as described above. The optimization procedure generates random birth, death, shift and connect proposals, which are accepted or rejected according to their posterior probability depending on the total energy change and the current annealing temperature [3]. As the algorithm proceeds, the track segments move around, link together and gradually 'freeze' into the final configuration.

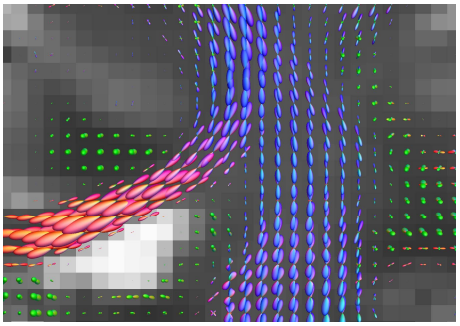
Fig. 2: Fibre ODF in the centrum semiovale.

RESULTS – Data of a single subject were provided by the NIH Human Connectome Project, WU-Minn Consortium (www.humanconnectome.org): 18 gradients at b=0s/mm^2, 3 x 90 gradients at b=1000s/mm^2, 2000s/mm^2, and 3000s/mm^2, 1.25mm isotropic voxel size [7]. The WM (fibre) response function is estimated as in [6] for each shell separately and then scaled with weight 0.1 (i.e., about 10 segments per voxel are required to reconstruct the signal). The isotropic CSF kernel is estimated as the mean MR signal of each shell in the ventricles. The GM kernel is currently defined as the isotropic part of the WM kernel. Using a segment length of 2mm and an exponential annealing scheme from $T_0 = 0.1$ to $T_1 = 0.001$ in 5 x 10^8 iterations, the reconstructed full-brain tractogram (Fig. 1) contains 2.37 x 10^5 tracks consisting in total of 2.26 x 10^6 segments. The fibre ODF and the estimated CSF and GM fractions are computed as ancillary results of the global tractography algorithm and shown in Figs. 2 and 3.

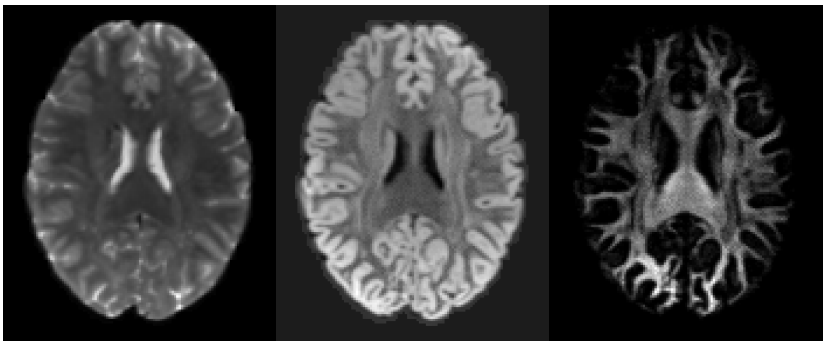
Fig. 3: Estimated CSF and GM fractions and the segment density (WM fraction).

DISCUSSION – The proposed method successfully reconstructs the main WM tracts in the brain, and in the process also recovers an estimate of the fibre ODF and the amount of CSF and GM. In this way, all of the information contained in the high-resolution, multi-shell data can be used directly, whereas spherical deconvolution techniques currently require to select a single shell (b-value). The fODF shown in Fig. 2 appears slightly more smooth than the result of CSD [6] (not shown), which we attribute to the spatial regularization imposed by the global tracking algorithm. However, Fig. 2 also shows that the radial projections of the corpus callosum are not fully recovered by our approach. The estimated CSF, GM and WM segmentations in Fig. 3 show hyperintensities in the respective tissues, although the GM fraction also increases in regions of crossing WM bundles. In crossings, the HARDI signal is more isotropic and therefore more easily captured by the GM kernel, which also explains the drop of the segment density in those regions. We currently attempt to overcome this limitation.

Additionally, global tractography explicitly ensures that the segment density (and by extension the track density) is more or less proportional to the magnitude of the q-space signal. Streamline tracking methods can not generally impose this property due to their dependence on the seed distribution, and therefore lose valuable quantitative information about track density and connectivity. As such, the global tractography framework can bypass the need for post-processing methods such as [8].

CONCLUSION – We introduced a method for global reconstruction of the tractogram from multi-shell HARDI data, based on *any* fibre response function represented in the SH basis. This work is a first step towards global fibre reconstruction of more general types of q-space data, and could serve to compare different microstructural models in a globally constrained setting.

REFERENCES – [1] Jbabdi and Johansen-Berg, *Brain Connectivity 1(3):169-183* (2011), [2] Mangin et al., *NeuroImage 80:290–296* (2013), [3] Reisert et al., *NeuroImage 54(2):955–962* (2011), [4] Fillard et al., *MICCAI 12(1):927–934* (2009), [5] Kreher et al., *Magn. Reson. Med. 60(4): 953–963* (2008), [6] Tournier et al., *NeuroImage 35(4):1459–1472* (2007), [7] Van Essen et al., *NeuroImage 80:62–79* (2013), [8] Smith et al., *NeuroImage 67:298–312* (2013).